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LASER GYROS AND FIELD DIAGNOSTICS

FINAL REPORT

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Final Report

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This report covers two areas of investigation:
1) New concepts of rotation sensing, and
2) New methods to time resolve electrical transients.

1. STUDY OF LASER GYROS

1.1. Introduction

Today's He-Ne laser gyro's have reached a ceiling in technical development, and dominate the inertial navigation market worldwide. Since the quantum noise limit of these lasers is approached, there is little room left for improvment. It is therefore appropriate to seek for alternate conceptions of laser gyros, rather than to attempt to push further the limits of an already nearly perfect technology. The goals to be seeked for the next generation of rotation sensors are:

- Smaller size,
- All solid state,
- Reduced noise (hence, higher accuracy).

The first two condition suggest the use of integrated opto-electronics. Unfortunately, solid state laser implies generally large scattering, hence a large dead band, and large homogeneous

broadening, which tends to make the ring laser operation unidirectional.

We have investigated several new concepts that offer various solutions to these problems:

a) use of degenerate four wave mixing to alleviate the lock-in (dead band) problem, as well as the tendency towards unidirectional operation.
b) Use of mode-locked semiconductor lasers, to restrict the critical region where coupling might occur, to the overlap region between counterpropagating waves.
c) use of a ring laser configuration with reduced spontaneous noise through destructive interference of the laser outputs.

We have started experimental measurements on the first two ideas. A theoretical study of the third concept has been completed (Appendix A).

2.2. Homogenously broadened lasers

A phase conjugated coupling between the counter propagating beams of a ring laser should reduce the lock-in threshold [1](Diels-McMichael 1982) and make an homogeneously broadened solid state laser a potential laser gyro candidate. As a result it should be possible to make a compact active laser gyro with solid state and optical integrated circuit lasers.

A CO_2 ring laser is used in this initial approach, because it offers more flexibility (variety of parameters to be adjusted) than any other laser. In the CO_2 laser under investigation, two nonlinear media are being studied for the DFWM: the gain medium itself, and near DFWM in InSb (two photon absorber).

The coupling between counterpropagating beams is restricted to their region of overlap, which can be very small if the

circulating energy is concentrated in ultrashort pulses. We are investigating this concept with mode-locked GaAs lasers.

The spontaneous emission noise can be interferometrically subtracted, if the gain consists of thin (<<) layers.

1.3. Description of the CO_2 laser

The CO_2 laser is mounted on a 2 m diameter rotating aluminum table, supported by an axial and radial ("Professional Instruments", Minneapolis) air bearing. Water and gas inlet and outlet, laser supply voltages, are fed through concentric tubes and mercury contacts shown in Fig. 1, allowing the laser to be operated during continuous rotation of the table. Details of the power and cooling distribution to the table can be found in the sketches of Appendix A.

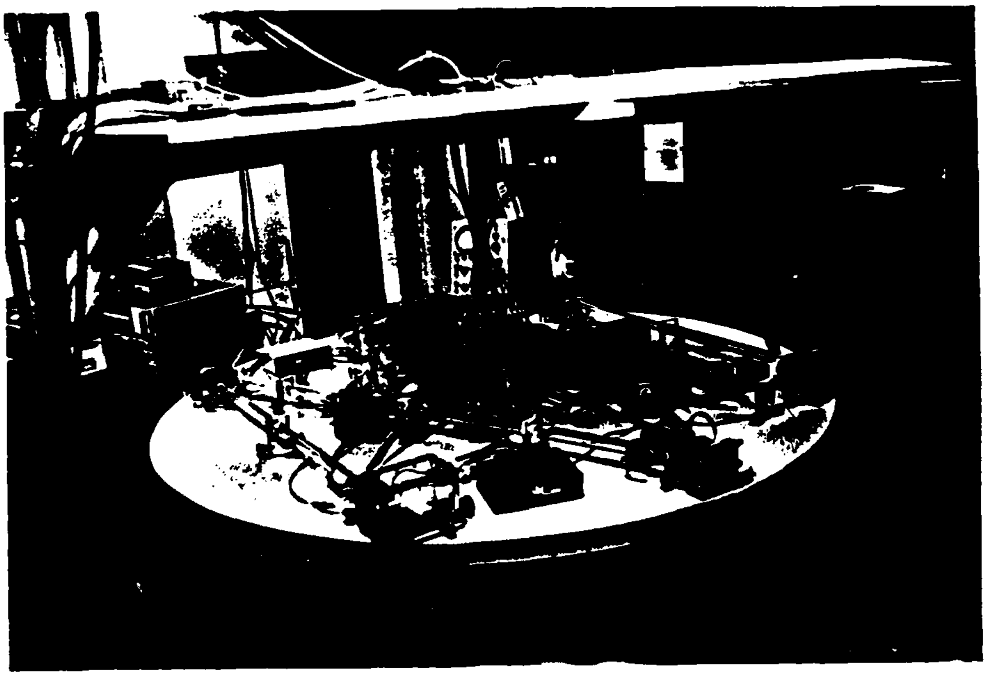


Figure 1a: the laser gyro platform

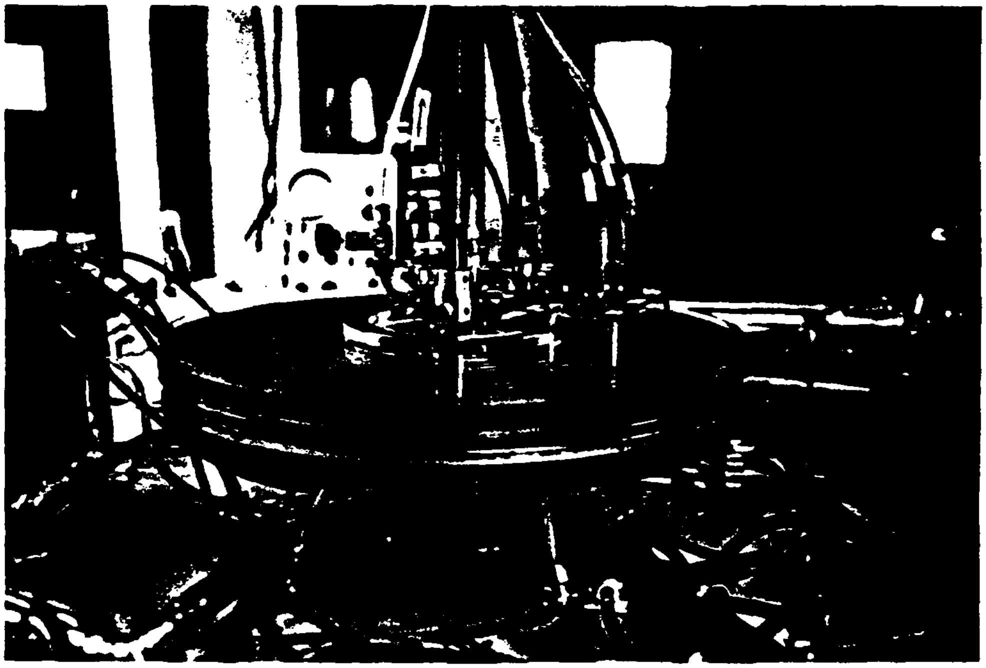


figure 1b: gas, water and power supply through the shaft

The CO_2 ring laser itself consists of 4 identical discharge tubes (1 m between electrodes) mounted in losange. The "pump" beams for DFWM are supplied by a "**W**" shaped linear cavity (Fig. 2). Polarizing beam splitters S_1 and S_2 isolate the two cavities (the beam in the linear "W" cavity being polarized with the electric field in the plane of the figure, orthogonally polarized to the beam of the ring laser). Electrical and gas currents flow in opposite directions in non adjacent sides of the ring, in an attempt to minimize gyro bias through gas and Langmuir flows.

In this first configuration, there is no solid intracavity element in the ring laser, in order to keep the linear scattering responsible for lock-in to a minimum. Only a small phase conjugated coupling between the counterpropagating beams, of the order of the backscattering coefficient, is required to reduce the lock-in threshold [1](Diels, McMichael 1982). The nonlinear

medium for the DFWM coupling is the gas (absorbing or amplifying) in the two discharge section common to the two laser cavities.

In a second configuration, a sample of InSb is introduced in the corner A common to both cavities. InSb is known for its large two-photon absorption, leading to a resonance in the DFWM coupling.

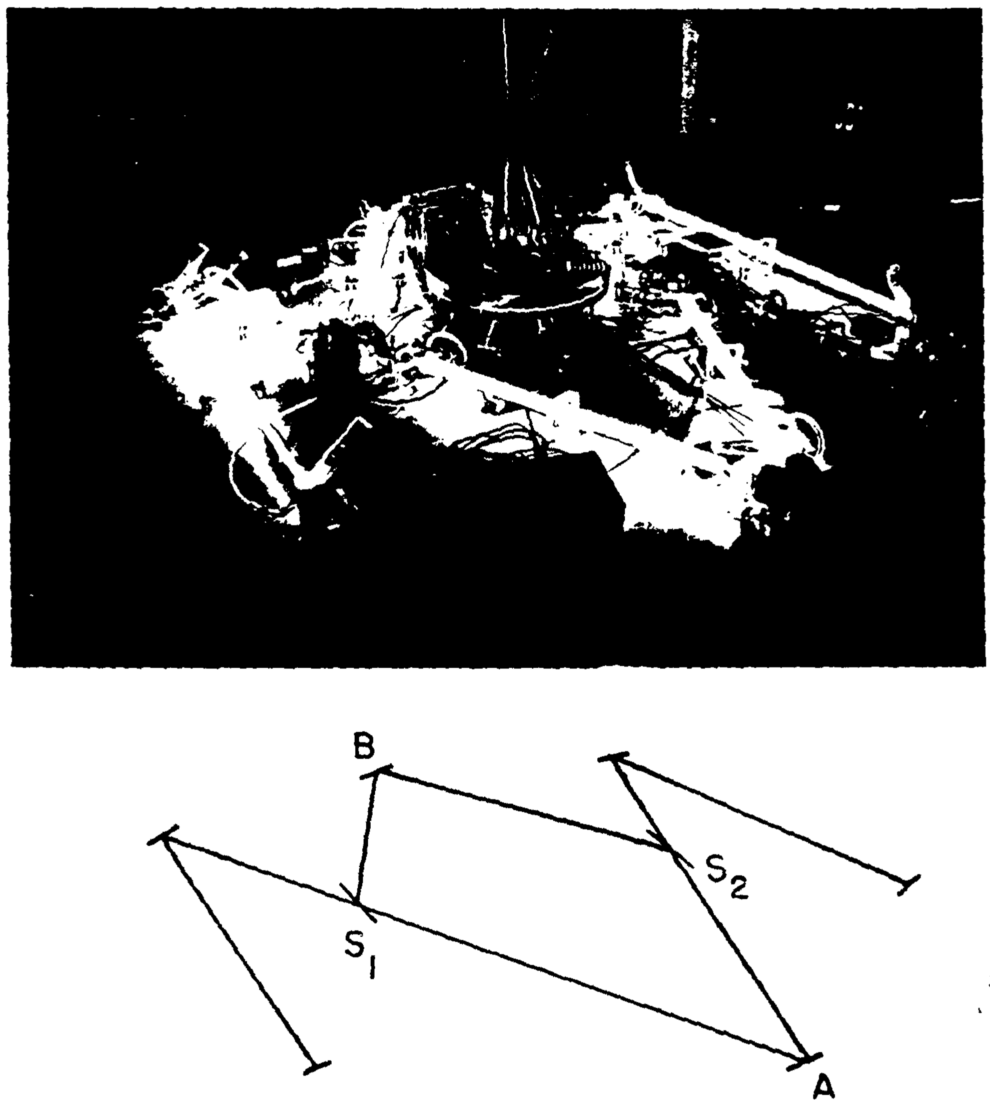


Figure 2: the CO_2 laser gyro

1.4. Measurement of the rotation rate and the gyro effect

The angular speed of the rotating table is measured by a speedometer based on the principle of the optical encoder. A

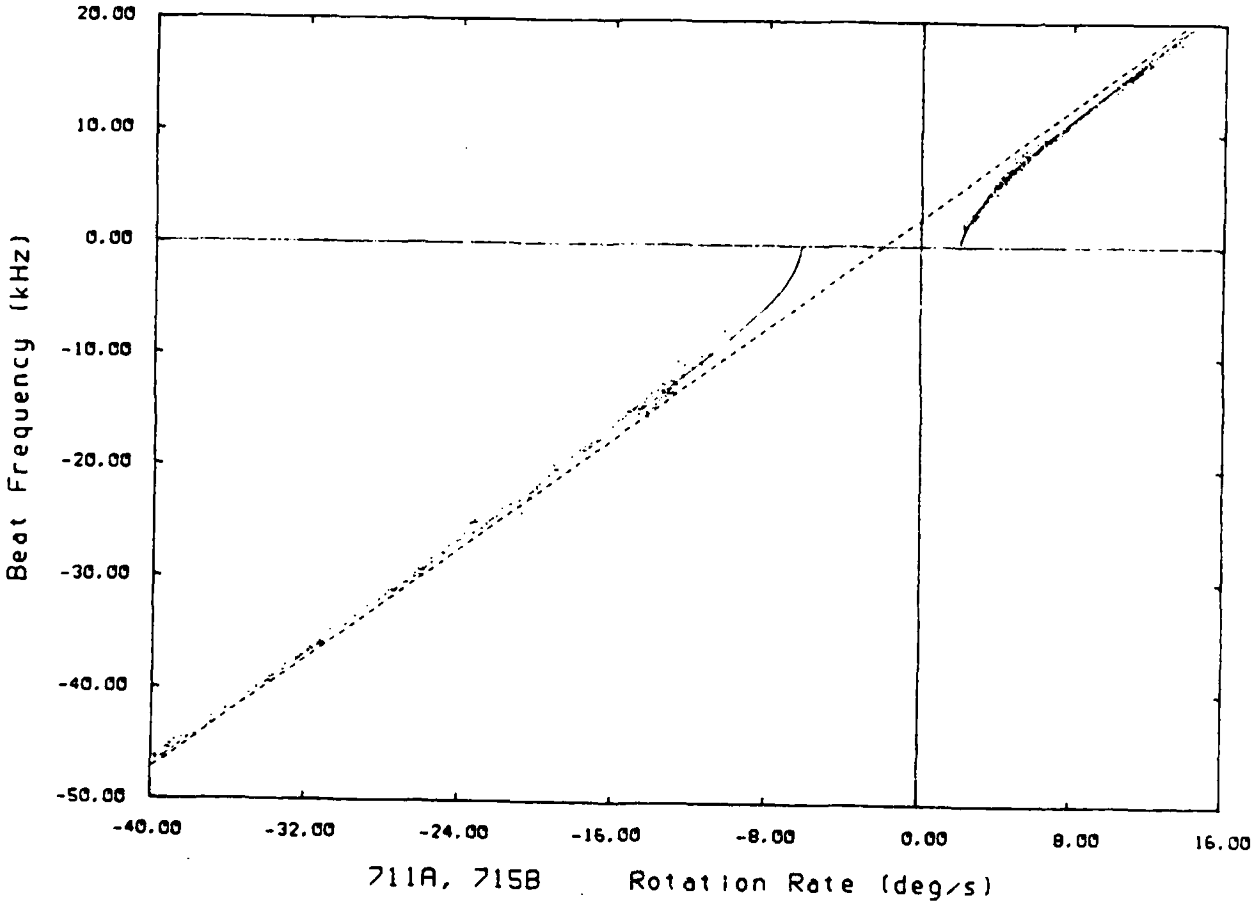
chopper wheel driven by the tableis used to interrupt the light path between an LED and a photodiode, thus generating a square wave signal with a frequency proportional to the rotation rate. This frequency is measured by a Hewlett-Packard 5345A frequency counter. The accuracy of the measured rotation rate is approximately 0.1 deg/s.

The outputs (B) (Fig. 2) of the laser are mixed on a lithium titanate pyroelectric detector. The detector output is monitored simultaneously by a HP 3585A spectrum analyzer and an oscilloscope. The digital outputs of the frequency counter and of the spectrum analyzer are collected by a Zenith 286 AT-compatible computer. The 3585A has a tunable counter feature that can be remotely programmed through the IEEE-488 bus to lock onto and count the frequency of any sufficiently strong signal within a user specified bandwidth. The measurement is averaged over a 0.6 s period, and is accurate to 0.1 Hz.

The Zenith computer controls the spectrum analyzer and counter by way of an IEEE-488 interface card purchased from IOtech. Inc. of Cleveland, Ohio. This card provides full remote control of the measurement devices. the system is programmed such that the operator initiates the taking of a datum, the computer then commands the devices to perform the appropriate operations. Upon completion of the measurement the values are communicated over the bus in digital form to the computer which reduces the data in real time, resets the devices, and displays the results for the operator to decide whether to keep the datum and/or continue data collection. Data thus obtained are stored for later analysis.

A theoretical fit of the data enables accurate determination of the lock-in rotation rate, the wavelength (independently checked by a Czerny-Turner IR spectrometer) and a rotation rate bias.

Figure 3 shows a typical gyro response, with a scale factor of 1.238 s-kHz/deg. The lock-in rotation rate is 4.17 deg/s, and the rotation rate bias is - 2.15 deg/s. A complete plot of beat frequency versus positive and negative rotation rates is shown in Fig. 4.



1.5. Four Wave Mixing with the CO_2 Laser

Intracavity four wave mixing with the CO_2 laser has proven to be a much more arduous task than originally anticipated. Two experimental difficulties encountered are:

a) having the linear and ring laser operating on the same rotational line;

b) stabilizing the backscattering in presence of the linear laser cavity.

With the gain plasma as nonlinear coupling between the two cavities, the total output power decreases when the two lasers are operating on the same transition. We have incorporated a grating in the ring as well as in the linear section to force operation on the same line.

Because of the large size of the laser and the small cross-section of the tubes, the ring cavity cannot be completely decoupled from the linear cavity, resulting in an increased dead band for the gyro. This is actually a desirable feature, since the measurement accuracy is better at higher speeds. However, in order for this new source of backscattering to have a well defined phase, the linear cavity length has to be stabilized to within a fraction of wavelength. Without the additional active stabilization piezoelements, some response has been observed within the dead band. However, it is essential to repeat these measurements with a control of the phase of the backscattering, before concluding that an actual reduction of lock-in has occured. An active feedback loop with PZT elements has been implemented to stabilize the long linear cavity. These modifications have significantly set back the start of actual measurements, which are still being made at this time.

The nonlinearities being presently tested are gain saturation and absorption saturation (in SF_6 and CO_2).

1.6. Two-Photon resonant four wave mixing

The next nonlinear medium under investigation is InSb, which is known to show very strong two-photon absorption at 10.6 micron. A 100 m thick sample has been prepared, polished, antireflection coated for 10.6 m. Unfortunately, preliminary measurements failed, because the small linear absorption of the sample produced sufficient heating to increase drastically the absorption coefficient, increasing further the temperature, until the sample became totally opaque. To solve this problem, the sample has been fitted with Peltier coolers, to dissipate the heat production by the CO_2 laser and to minimize the absorption. Here again, the additional hardware requirements and increased complexity of the system has pushed back the data acquisition to 1990.

1.7. Semiconductor Laser Gyro

It is the coupling between counterpropagating beams in the gyro that is responsible for the lock-in phenomenon. One possibility to reduce that coupling - hence the dead band of the gyro - is to minimize the overlap between tehse beams by using short laser pulses. Ideally, the pulse overlap is to occur in a region of minimal scattering. The first design problem is thus to prevent the pulses from overlapping in the laser gain medium. One possibility - that we are investigating - is to use a type of coupling increasing the overlap probability of the two pulses without a tendency to lock their phases. Degenerate four wave mixing provides such a coupling.

We have constructed a GaAs ring laser, mode-locked through gain modulation. (the GaAs laser is powered by a frequency synthesizer, a power amplifier and a comb generator) A considerable effort has been devoted in the last year in developing high quality antireflection coatings for these GaAs

lasers. (in our CHTM coating facilities) It is precisely the technical difficulties in achieving satisfactory performances for these coatings that has delayed up to now the completion of this new type of gyro. To study the gyro response, the rotation is simulated by a Faraday rotator. (a 10 cm SF_5 glass in a magnetic field)

In the cavity sketched in Fig. 5, a mixed crystal $CdSe_{0.5}S_{0.5}$ is used as nonlinear (two-photon absorbing) element. The two photon absorver is common to both the ring cavity and a synchronous linear cavity. In the two photon absorber, four pulses meet: the two counter propagating pulses of the ring laser, and two counterpropagating pulses of the linear laser.

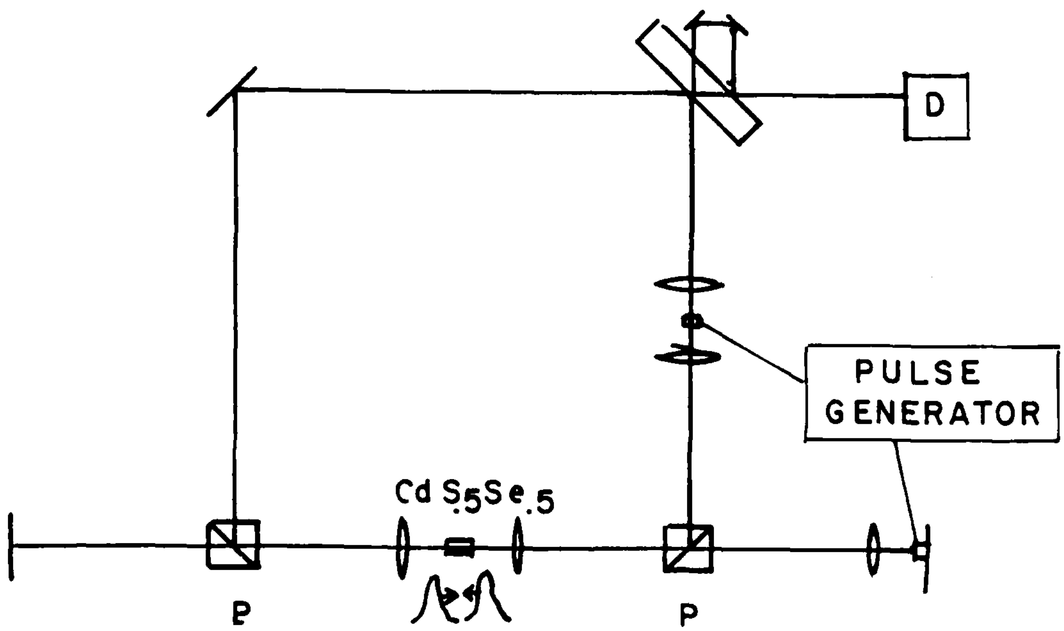


Figure 5: the semiconductor laser gyro

1.8. New Laser Gyro Concepts

We have been looking for alternate laser gyro concepts for which the spontaneous emission could be significantly reduced. We have shown that the spontaneous emission can be interfero-

metrically decoupled from the quantity measured from the laser. This was demonstrated in a simple test with a thin layer of fluorescent dye[2]. A laser medium consisting of layers thinner than the wavelength could be thus used as a gyro from which the measurement could be made free of stimulated emission. The stimulated emission process itself would provide a coupling between counterpropagating waves. We have shown by computer calculations that such a coupling can be eliminated by a proper choice of backscattering conditions.[3] Estimates made for "stoichiometric lasers" also known as "high concentration lasers" such as $KNdP_4O_{12}$ laser material grown on $KLaP_4O_{12}$ substrates show a reduction in noise factor by a factor $2\ 10^{-3}$, which implies that the accuracy in rotational measurements would be enhanced by a factor of 500. (Appendix A)

2. ULTRAFAST PROBING OF ELECTRICAL CIRCUITS

2.1. Introduction

The purpose of this part of the research is to study new diagnostic techniques for ultrafast integrated circuits. In particular, the new methods should provide a **single shot, instantaneous** mapping of the field distribution in complex and fast integrated circuits. The time window being considered is subpicosecond.

The ideal method should exhibit a large field induced change in an optical property, detectable through a very thin layer (in order to probe the local edge fields of the conductors, with minimum spatial averaging). The response of the probe material should be uniform over a large area. A last requirement of the method is a good contrast (i.e. zero signal in the absence of field) and linearity.

The methods that have been considered are:

a) electric field induced spectral absorption and fluorescence shift of dyes
b) field induced second harmonic generation in PLZT
c) electro-optic effect in PLZT

For the first method, we have first selected and investigated biological stains, known for their large electrochromic response. Spin coating under electric field was attempted next with several dyes to deposit oriented layers on the circuit under investigation.

Probing with PLZT requires a fs laser source tunable around 750 nm, which we have constructed.

Initial probing is local. In preparation for the two dimensional single shot technique, we have assembled a copper

vapor laser pumped amplifier, and a two dimensional data acquisition systen with reticon and image intensifier. Femtosecond resolved imaging has been demonstrated. The same accessories have been used to develop a single shot instrument to characterize fs signals in amplitude and phase.

2.2. Induced spectral absorption shifts in dyes

In a series of experiments detailed in the annual report of 1988, we duplicated the biological tests of absorption shifts across a membrane, used to determine the electric field response of the dyes called "probes of potential". Instead of natural cell membranes, we chose to prepare cell membranes in the form of "liposomes". Liposomes are lipid bilayers organized in the form of perfect spherical vesicles. Dyes were inserted in the membrane of these liposomes. A dc electric field was applied to this membrane by modibying the relative concentration of K^+ anions inside versus outside the spheres. The absorption and fluorescence spectra were recorded after and before application of the potential difference (across the membrane).

The conclusion to draw from extensive measurements is that the observed "potential induced spectral shift" results generally from a potential dependent redistribution of the equilibrium concentration of dye on the membrane, the solution and even the walls of the container. Indeed, the "field induced spectral shift" with Oxonol VI was seen to be dependent on the surface tension of the contained glass. The very large (0.03 nm.cm/kV) "spectral shifts" that were indeed observed never reflected a true "Stark shift" or Electrochromism.

High Speed Testing

The first testing set-up consisted in an avalanche photodiode as a source of electrical pulses, terminated into 50 through a coplanar transmission line (Fig. 6).

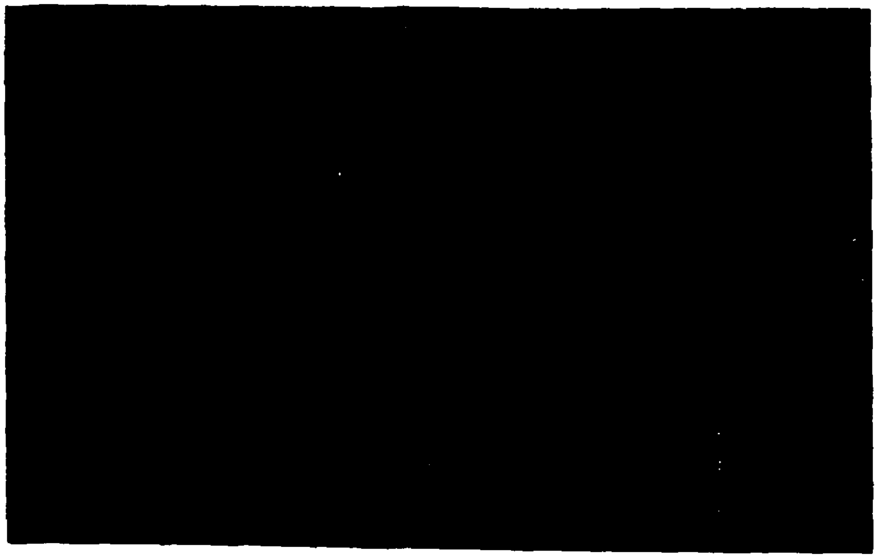


Figure 6: Coplanar testing circuit. The field detecting dye is spread over the surface of the circuit.

With the dye DTDCI in n-propyl metacrylate polymer, spin coated on the surface of the circuit of Fig. 6, we observe the change in probe transmission shown in fig. 7. The electric pulse was 1.5 V peak, across a gap of 20 micron. The observed change in transmission, probed by a synchronously pumped dye laser, is of the order of 10^{-6}. Clearly, there is a need for dyes with much higher field induced shifts. We intend to repeat these measurements with dyes such as MNA, which are known for their extremely high nonlinearity.

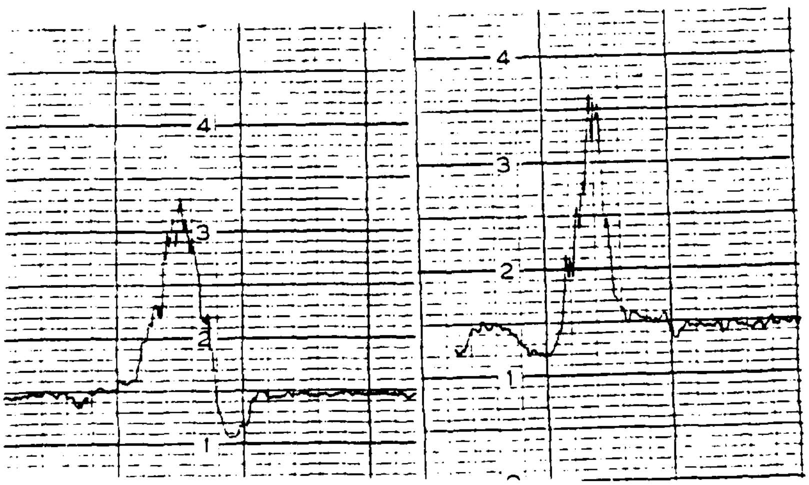


Figure 7: Change in probe transmission induced by a 80 ps pulse.

Integrated circuits were prepared on silicon and semi-insulating GaAs. An example of the mask used is shown in Fig. 8. These circuits incorporate a photoconductive switch (to be triggerec by a strong fs pulse), and an area with a narrow gap, tp be covered by a thin layer of dye, for probing of the electric field. Similar circuits are to be used for testing of thin films of PLZT.

2.3. PLZT

Thin films of PLZT (La- doped lead zirconate titanate) sputtered o nglass substrates can be used to probe the local fields at the edge of conductors of an I.C. DC field induced second harmonic generation was recently measured at the CHTM. The response time could not be resolved beyond 1 ns risetime. We have started testing this material for circuit probing in the picosecond to subpicosecond range. The physical mechanism involved is a field induced phase transition, in which a cubic centrosymmetric phase is transformed into a distorted lattice lacking center of symmetry, thus capable of generating a second harmonic. To test this property of PLZT in the fs range, we have started the development of a near infrared hybridly mode-locked dye laser. Details of this laser development have been published in the Journal of Modern Optics.[4]

2.4. FS resolved 2D images

Another development related to the testing of the IC is the ability to time resolve two-dimensional images. We demonstrated this capability by up-converting test patterns in a urea crystal. Temporal resolution of the order of 50 fs was achieved by using a reference pulse, orthogonally polarized to the image beam, in a second harmonic generation configuration type II.
The images were analyzed with an image intensifier coupled to a reticon camera. Since the sensitivity of this technique is proportional to the square of the laser pulse intensity, a new

Figure 6: Coplanar testing circuit. The field detecting dye is spread over the surface of the circuit.

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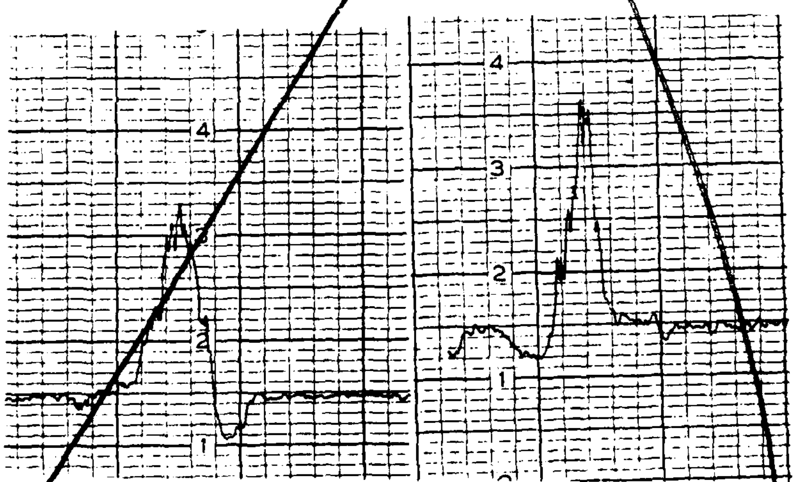

Figure 7: Change in probe transmission induced by a 80 ps pulse.

design of copper vapor laser pumped dye amplifier was developed, and used for the time resolved imaging.

2.5. Diagnostic Techniques

In order to study the dynamics of nonlinear effects, as well as for the development of the laser sources themselves, there is a need for a diagnostic technique capable of time resolving the pulse shape and phase modulation. For the femtosecond time scale we have developed a unique capability to measure the time variation of the amplitude and phase of a repetitive or single shot signal.[5-8] The basic principle of the technique is to apply a known, reversible transformation (for instance propagation through glass) to the pulse to be measured, such as to create a stretched signal that can be completely determined through interferometric cross-correlation with the original short signal. The latter is recovered by applying (numerically) the inverse transformation to its stretched out version. this technique can be extended to the picosecond domain by substituting to the glass, dispersive delay lines.

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8. M. Lai and J.-C. Diels, "Ring laser configurations with reduced spontaneous noise through destructive interferences of the laser outputs", submitted to Phys. Rev. A (1990)

APPENDIX A

Ring laser configuration with reduced spontaneous noise through destructive interference of the laser outputs

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ABSTRACT

Thin layered gain media in a ring cavity can lead to detection devices free of spontaneous emission noise. A theoretical analysis and a physical explanation for the destructive interference of the spontaneous emission in one of the laser outputs are presented.